

6.—THE PHYSICAL PROPERTIES OF MANGANESE STEEL.

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(With Two Plates—xxviii.-xxix.)

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The remarkable magnetic properties possessed by an alloy of 75 per cent. iron and 25 per cent. nickel were pointed out in 1899 by Hopkinson.¹ It was shown that such an alloy was non-magnetic at room temperature, but if cooled down in a freezing mixture to below -20°C ., it became magnetic and remained magnetic while the temperature was raised to nearly 600°C . Iron and nickel form, as the freezing point curve shows, a series of homogeneous solid solutions and a compound, probably Fe_2Ni^2 . The temperature of the β - α magnetic inversion (Ar_2) of iron is lowered by the addition of nickel, and that of nickel is raised by the addition of iron. All the alloys with less than 25 per cent. nickel have two transformation or critical temperatures, the points Ar_2 and Ac_2 being distinct and giving a certain hysteresis of the magnetic transformation. In the case of the eutectoid alloy with 25 per cent. nickel, the lag in the transformation temperature is about 600°C .

Investigations made in 1910 by J. G. Gray and the author indicated that manganese steels showed somewhat similar properties. Various causes delayed the full investigation of this subject, and so the present paper summarises results obtained over a period of some 15 years.

Manganese has become a highly important element in connection with the metallurgy of steel, and so the results of the researches have enhanced in value. It was in 1774 that Gahn isolated the metal manganese, but it was the experiments of Mushet in the middle of last century which resulted in the addition of manganese to Bessemer's blown metal to produce a very tough and workable steel. Sir Robert Hadfield in the year 1883 was the first to show that a steel containing 12 or 13 per cent. of manganese with 1.0 to 1.5 per cent. of carbon was practically non-magnetic, and that quenching rendered it remarkably tough instead of hard and brittle.

The tests to be described have been carried out on a graded series of steels specially prepared by Sir W. G. Armstrong, Whitworth & Co., and with a manganese content varying in steps from 0.2 per cent. to 12.5 per cent. The carbon content was almost constant at 0.7 per cent., and the sulphur at 0.02 per cent., while with increasing manganese the silicon rose from 0.1 to 0.5, and the phosphorus from 0.012 to 0.05 per cent. The silicon and phosphorus increased through being added as an impurity in the manganese, but tests carried out by J. G. Gray and the author² show that such variation would not appreciably affect the magnetic properties of the steels.

The peculiarities in the magnetic behaviour of the steels begin to grow marked with a manganese content of about 6 or 7 per cent. After annealing a specimen of such steel at 900°C ., the material gives an intensity (I) of magnetisation of only 72 c.g.s. units in a field (H) of 50 gauss. When the metal is lowered to the temperature of liquid air (about -190°C .) we obtain a value of I of 212 for the same applied field $H = 50$. On warming up to room temperature we find that the value of I is now 342 for $H = 50$, and, if the cooling and heating have been sufficiently slow, the material is completely reversible, with I varying between 342 and 266 as the temperature is altered from 15° to -190°C . The liquid air treatment has thus resulted in transforming the specimen from a feebly magnetic state to one of good magnetic quality. In the final condition the effect of immersion in liquid air is that found in ordinary carbon steels,³ viz., a reduction of the susceptibility for low and medium fields, and an increase for fields exceeding $H = 250$ when the specimen is cooled from 15° to -190°C . If we define the magnitude of the transformation which has been brought about in the annealed steel by the liquid air treatment as the percentage by which the final exceed the initial susceptibilities corresponding to room temperature, we get the following results for various values of the applied magnetising field.—

Applied field	5	10	20	50	100 gauss.
Transformation	375	300	260	230	205 per cent.

When the manganese content is as low as 1 per cent., no measurable change in magnetic quality is brought about by the liquid air treatment of the annealed metal. With increasing content to 6.5 per cent. manganese the transformation increases steadily in amount, but afterwards falls off slowly as the manganese is raised to 10 per cent., and more rapidly with further increase to 12.5 per cent. Steels containing 10 per cent. and more of manganese are only feebly magnetic in the annealed condition.

It is interesting to note that manganese steels with more than 2 or 3 per cent. of manganese are more magnetic at somewhat elevated than at ordinary temperatures. Thus, in a field $H = 20$, an annealed 6.5 per cent. manganese steel had an intensity of magnetisation (I) of 16 at 15°C ., 25 at 230° , 31 at 490° , 125 at 630° , and 55 at 670°C . For $H = 100$, the corresponding values of I were 139, 146, 153, 282, and 112. This steel became non-magnetic when a temperature of 725°C . was attained. In the transformed state the same phenomenon is observed. Thus for $H = 20$ we have I 80 at 16°C ., 110 at 210° , 123 at 320° , 150 at 460° , 290 at 610° , 300 at 660° , and 103 at 690° , while for $H = 100$ I at the same temperature takes the values 576, 660, 750, 730, 650, 485, and 238. This transformed steel becomes non-magnetic when heated to 730°C .

Much of the apparently anomalous behaviour of the manganese steels may be satisfactorily explained if we consider the influence of manganese on the iron-carbon system. Manganese is isomorphous with gamma-iron and forms solid solutions with it.⁴ Thus the addition of manganese to a carbon steel has the effect of retarding the inversion of the non-magnetic gamma-iron into magnetic alpha-iron. A manganese steel under ordinary conditions will therefore to some extent exhibit the structure which would be obtained by the ideal quenching of a carbon steel at a temperature of, say, 900°C .,

that is, at a temperature at which it would consist of a solid solution of carbon or carbide of iron in gamma-iron.⁵ The term austenite is commonly applied to this solid solution and will be employed here for the sake of brevity. The addition of the manganese, however, does not completely suppress the inversion at temperature A_{r_2} into alpha-iron, just as the actual quenching of a carbon steel will not altogether stop the change into magnetic iron. Consequently a manganese steel after ordinary treatment will consist partly of non-magnetic gamma-iron and partly of magnetic alpha-iron, the amount of alpha-iron present being less the greater the manganese content—other conditions being identical. On the whole, therefore, the manganese steel is less magnetic than a simple carbon steel with the same relative proportions of iron and carbon. But the manganese steel is not in a true equilibrium condition. The gamma-iron which it contains is not stable at ordinary room temperature, and has only had a quasi-stability conferred upon it by the presence of the manganese. But for this restraining factor the gamma-iron would all have been converted into alpha-iron at a temperature of about 730°C. for a steel containing about 0.7 per cent. carbon. The further we cool the steel below this temperature, the less is the metastability of the austenite and the more of this phase will undergo inversion. The transformation from austenite into pearlite (the well known eutectoid constituent of ordinary steels) is not direct, the material passing through certain intermediate stages of resolution, which, as they exhibit characteristic microstructures, have had distinctive metallographic names given them. The more important transition stages are hardenite, troostite, and sorbite. The first of these is a non-magnetic condition, but the last is decidedly magnetic. The feeble magnetism of the 6.5 per cent. manganese steel is therefore explained if we can show that iron is retained to some extent in the gamma condition down to room temperature, that is to say, if the annealed steel exhibits a martensitic structure. This, as will be shown later, has been found to be the case. We shall also expect the intensity of magnetisation of this steel for any definite applied field to be zero about 730°C. Thereafter, if the steel be cooled to any temperature $t^\circ\text{C}$., and tested at a fixed temperature $T^\circ\text{C}$. (not less than t), the value of I as measured at T° will be greater the lower value of t . That this is in strict agreement with fact is shown by the following table of the values of I for $H = 100$:—

$T^\circ\text{C}$.	$t^\circ\text{C}$.	I .
15	15	139
15	0	257
15	—190	576

Similar results were obtained for the steels with manganese content less than 6.5 per cent., but when the amount of manganese became as low as 1.5 per cent. the steels showed very little evidence of transformation at all. The effect was also marked in steels with more than 6.5 per cent. manganese until the manganese content became so large as to leave the metal almost non-magnetic in all conditions.

In order to show that the transformation effected by the liquid air treatment was produced by the conversion of gamma into alpha iron, specimens of the annealed steel were examined under the microscope before and after cooling to -190°C . Some of the photomicrographs obtained are shown in the accompanying plates. For etching, a one per cent. solution of nitric acid in alcohol was employed and gave satisfactory results.

With all the steels containing less than about 1 per cent. of manganese, both before and after cooling to -190°C ., the steel consisted of a pearlite groundmass and alpha-ferrite filaments; that is, alpha-iron without any gamma-iron, and hence no transformation was to be expected in the magnetic tests.

Plate xxviii., figs. 1 and 2, are micrographs of a 1.32 per cent. manganese steel. Both exhibit the same general type of structure, viz., massive pearlite and alpha-ferrite filaments. The pearlite in the annealed specimen is not, however, so well laminated as we find it in an ordinary carbon steel. It is rather of a sorbitic nature, that is to say, it is the decomposed austenitic solid solution which has not been completely resolved into pearlite. The manganese is showing in this case its power to check the conversion of gamma- into alpha-iron. After cooling to -190°C ., the pearlite is better laminated, that is, the metastability shown in the sorbitic structure has been almost entirely removed and the resolution into true pearlite is now practically complete. As the sorbitic and the laminated pearlite both consist of alpha-iron there is no distinct difference in the magnetic quality of this steel before and after cooling to -190°C .

Plate xxviii., figs. 3 and 4, are photomicrographs of a steel containing 2.57 per cent. of manganese. Again we have a structure containing alpha-ferrite and pearlite. In the annealed specimen, however, the pearlite is all sorbitic and there is a distinct indication of the needle-shaped structure which is characteristic of martensite (non-magnetic gamma-iron). The pearlite shows both dark and light shading, and there is very little free ferrite. After the cooling to -190°C ., the specimen in its transformed condition exhibits quite a different structure. The martensitic appearance is not noticeable, and a transition product—probably troostite—appears as minute dark amorphous patches. The iron is now therefore entirely or almost entirely alpha-iron, and hence the magnetic susceptibility of the steel is augmented by the transformation of the original admixture of gamma-iron into alpha-iron.

Plate xxix. shows the microstructure of a 6.50 per cent. manganese steel. In the annealed specimen the chief feature is the interlaced structure of acicular martensitic constituents (gamma-iron). The white groundmass is partly the manganese carbide with any free gamma-iron. It will be observed that the martensitic needles orient themselves so as to build up a pattern of more or less perfect equilateral triangles. The broad dark bands are very possibly composed of hardenite (which contains no alpha-iron). After the specimen has been immersed in liquid air it presents a very marked change of structure consisting of a treble formation. The white patches are almost completely freed alpha-ferrite. The main groundmass is the double carbide $(\text{MnFe})_3\text{C}$ with some partially undecomposed hardenite which is most probably in the transition form of troostite, showing as a few minute black dots.

Plate xxviii., figs 5 and 6, give the appearance of a 9.87 per cent. manganese steel. In the annealed state about 80 per cent. is a groundmass of a solid solution (austenite: gamma-iron). There are also minute blue segregations—probably manganese sulphide—with which are associated amorphous black patches of troostite. After cooling to liquid air temperature, the solid solu-

tion is largely decomposed, and, as a result, much of the original gamma-iron is now found in the form of troostite (alpha-iron). This specimen, therefore, although always feebly magnetic shows the same type of transformation as the 6.50 per cent. manganese steel.

If the hypothesis is correct that the magnetic transformation of the manganese steels produced by cooling to liquid air temperature is representative of a transition from austenite and hardenite (both containing gamma-iron), then a carbon steel ideally quenched at 900°C., or above that temperature, should show precisely the same kind of effect. This will be evident if we consider the structure of such material. A high carbon steel, after quenching at about 1,100° C., shows polyhedral austenite with hardenite needles, and there is little or no magnetic iron present. The steel is in this condition only very feebly magnetic. A considerable transformation is, however, effected by immersion of the specimen in liquid air, as will be seen from the following table, giving the results of tests carried out at 15°C.:—

		Intensity of Magnetisation, I.	
		$H = 40.$	$H = 200$
Before Liquid Air Treatment	84	487
After Liquid Air Treatment	100	635

This test seems to establish the accuracy of the theory advanced above to account for the curious transformations occurring in manganese steel.

The investigations described in the foregoing throw considerable light on the origin of many of the remarkable properties of manganese steel. The alloy is one in which the heat treatment is all important, and by proper variation of this treatment the alloy can be adapted to a very wide variety of purposes. In the toughened condition a tensile strength rising to 60 or even 70 tons per square inch is obtainable, with a ductility indicated by an elongation of 50 to 68 or 70 per cent. The remarkable feature is that resistance to wear by abrasion increases with the severity of the service to which it is applied, because the slightest deformation of the steel is accompanied by a considerable increase in hardness. Its use for tramway and railway points is at once indicated, as indeed is its application in all cases where toughness and ductility are called for in steel. In the early days of the use of manganese steel, failures may have been experienced, but these undoubtedly were due almost entirely to ignorance of the proper heat treatment. Now that the heat treatment and its effect upon the structure and constitution of the alloys have been determined, a wide extension of the employment of this special steel is certain, and countries possessing deposits of manganese free from deleterious impurities have a valuable asset.

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